CHAPTER 7

EXPERIMENTS ON GRAPHITE SPECIMENS OF DIFFERENT DENSITIES HAVING VARIOUS SURFACE ROUGHNESSES WITH THE BINOCULAR STEREO MICROSCOPE

7.1 Introduction

Main goal of this research work is to quantify the surface finish of carbon – carbon composite with the help of non physical contact method, i.e. to evaluate the average surface roughness parameter of carbon – carbon composites from the optical surface roughness parameters of images of carbon – carbon composites. If a stylus type instrument is used to measure the roughness then the finished surface of carbon – carbon composites is deteriorated due to force implied by the stylus during measurement. So many disadvantages are also associated with conventional stylus measurement method. Hence image processing method is used for this purpose.

To achieve the above goal, the database must be generated with the same class of material, i.e. graphite. Here the machined surfaces of graphite specimens are prepared which are having different densities. Experiments are performed on these specimens.

7.2 Objective of the Experiments

To establish the methodology for surface finish measurement of carbon – carbon composite class of materials, experiments are carried out on machined surface of high density graphite specimens. Machined surfaces of graphite specimens are obtained by controlling the cutting parameters (speed and feed) on vertical machining (VMC-850). Complete analysis is carried out with the help of image processing tool of MATLAB.
7.3 Experimental Work

7.3.1 Materials

The material used for this investigation is graphite specimens having the different densities. Graphite, a layered compound, is one of the allotropes of carbon crystalline exhibits the properties of a metal and a non-metal, which makes it suitable for many industrial applications. Graphite holds the distinction of being the most stable form of carbon under standard conditions. Graphite is a soft material even though the hardness within the atom layers approaches that of diamond. The metallic properties include thermal and electrical conductivity. The non-metallic properties include inertness, high thermal shock resistance and lubricity.

Graphite is mostly consumed for steel making, brake linings, fuel cells, and brushes for electric motors. It is also used as refractory material. Other significant uses of graphite in carbon fiber reinforced plastics, in heat resistant composites such as reinforced carbon-carbon composites. Products made from carbon fiber graphite composites include space age applications, fishing rods, golf clubs shafts, bicycle frames and pool sticks. Graphite foils use in valve packing and gaskets. Graphite is critical for many industrial applications, such as dies for continuous casting, rocket nozzles, and heat exchangers for the chemical industry.

7.3.2 VMC - 850 Machine

The experiments are conducted on Vertical Machining Center machine - 850, Jyoti, Rajkot made. It is CNC SIEMENS SINUMERIK 810 D solution line having AC spindle drive. Figure 7.1 shows the VMC - 850 machine used for the experiments.

7.3.3 CCD Camera

To grab the clear color image, Samsung, Korea made SDC - 313 B is used. This CCD camera has high resolution. It has high horizontal resolution of 530 TV lines. Total pixels are 795 (H) × 596 (V) and effective pixels are 752 (H) × 582 (V).
Figure 7.1 VMC -850 (Vertical Machining Center – 850)
7.3.4 Binocular Stereo Microscope

To obtain the quality images, Binocular stereo microscope, Model: RSM – 4, Radical Instruments, Ambala, made is used. This model has eyepiece of fixed WF 10x. Objectives head can be set either to 2x or 4x. Incident light is moved with objective head. Figure 7.2 shows the binocular stereo microscope with CCD camera. Figure 7.3 shows the graphite specimen machined on the VMC – 850 machine.

7.3.5 Stylus Roughness Measuring Instrument

For these experiments, to measure the average surface roughness parameter, ‘Ra’, portable Surface Roughness Tester (figure 7.4), Model: Surftest SJ-201, Mitutoyo made is used. Measuring force is 4mN. Diamond material stylus having tip radius 5μm (200 μinch). Radius of skid curvature is 40 m.m. Stylus roughness tester has a resolution of 0.000125 μm / 0.00492 μin. Filter is 2RC type.

This investigation is carried out under the following conditions:

1. The machine used for machining purpose is Vertical Machining Center -850 (VMC – 850).
2. Machined surface is obtained with help of 12 mm, four fluted end mill.
3. The material used for this work is graphite specimens having different densities.
4. Images of machined surface graphite specimens are grabbed with binocular stereo microscope with CCD camera.
5. Image analysis is done with software tool image processing of MATLAB.
6. Stylus roughness ‘Ra’ is measured for each specimen with stylus roughness tester after grabbing the image of each.

7.4 Planning of Experiments

These experiments are carried out with 1 mm or 2mm of depth of cut of machining. The process parameters chosen for machining of each graphite specimen having different density are the combination of different speed (rpm) and feed (mm/min). Basic aim is to
Figure 7.2 Binocular stereo microscope with CCD camera and graphite specimen
Figure 7.3 Machined surface of graphite specimen

Figure 7.4 Stylus roughness measuring tester
acquire the machined surface of graphite specimen having different roughness. To get this, machining is done on VMC – 850 with 12 mm, four fluted end mill.

According to the capability of VMC – 850 machine available and general recommendation of machining conditions for graphite specimens, the different parameters selected are shown in respective tables.

Experiments are carried out on graphite specimens of different densities: 1.7136 g /cc, 1.999 g/cc, 1.705571 g/cc, 1.643197 g/cc, 1.630556 g/cc, 1.541 g/cc, 1.7082 g/cc, 1.8478 g/cc and 1.45 g/cc.

For each image of above mentioned specimens, following analysis are carried out using MATLAB.

1. Preprocessing (Filtering)
2. Histogram Analysis
3. Fourier Analysis (Power Spectrum)
4. Estimation of Optical Parameters, Arithmetic Average of Gray Level Ga (before applying filter) and Gaf (after applying filter).
6. Estimation of Governing Equation which Shows the Relationship between ‘Ga’ and ‘Ra’.
7. Estimation of Governing Equation which Shows the Relationship between ‘Gaf’ and ‘Ra’.
7.5 Experiments Carried out on Graphite Specimen having Density 1.7136 g / cc

7.5.1 Experimental Procedure

Graphite specimen having density 1.7136 g / cc is machined on vertical machining center (VMC-850) with 12mm, four fluted end mill. Various surface roughnesses are obtained by controlling the machining parameters i.e. different speeds and feeds on VMC machine.

According to the capability of VMC – 850 machine available and general recommendation of machining condition for graphite, the following parameters shown in table 7.1 are selected.

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<th>S no</th>
<th>Speed (rpm)</th>
<th>Feed (mm/min)</th>
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<td>6</td>
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</table>

The depth of cut of machining is set at 1mm. The images of these machined specimens are grabbed by high resolution color CCD camera (Samsung SDC-313B) having effective pixels 768 (H) x 494 (V) with binocular stereo microscope (RSM 4).

Low pass filter is applied to all images. Histogram analysis and evaluation of optical surface roughness are carried out. Power spectrum is also obtained. These analyses are done with the help of image processing tool of Matlab. After completing the mentioned analysis, the arithmetic average roughness parameter is obtained for all specimens with the help of stylus roughness tester. Correlation is found out between measured stylus parameter and optical parameter.
7.5.2 Analysis of Result and Discussion

Analysis of each image is carried out. Here the images of graphite specimen (density 1.7136 g / cc) having stylus roughness, ‘Ra’ of 1.8267 μm and 4.8 μm are shown in figures 7.5 and 7.6.

7.5.2.1 Histogram Analysis

Gray scale analysis technique has been used for surface characteristic which is known as histogram. Histogram drawn shows the variation of grey level intensity as per the surface roughness of the surface. It shows the occurrence (frequency) of grey level intensity over the surface. Figures 7.7 and 7.8 show histograms of images having different surface roughness.

As the surface becomes smoother, there is an increase in the frequency of larger value intensity. In histogram, left side shows the smaller value of intensities and right side shows the larger value of intensities. As surface becomes smooth, reflectivity increases, resulting in higher value of frequencies for larger gray value intensities. In figure 7.8, rougher surface having surface roughness Ra = 4.8μm, there is a dominance of gray level 175 approximately having frequency (number of times each gray value occurs in image) 5000. As well as rougher surface has non uniform histogram compared to smoother surface. However in the case of relatively smoother surface having surface roughness Ra = 1.8267 μm, it is observed from figure 7.7 that 175 value of gray level is having 12000 frequency.

So from histogram one can judge that whether the surface is relatively smooth or rough. Histograms have the limitation that they carry no information regarding the relative position of the pixel intensities with respect to each other.
Figure 7.5 Image of graphite (density = 1.7136 g/cc) having Ra = 1.8267 μm

Figure 7.6 Image of graphite (density = 1.7136 g/cc) having Ra = 4.8 μm

Figure 7.7 Histogram of graphite (density = 1.7136 g/cc) having Ra = 1.8267 μm

Figure 7.8 Histogram of graphite (density = 1.7136 g/cc) having Ra = 4.8 μm
7.5.2.2 Fourier Analysis (Power Spectrum)

The 3-D perspective of the power spectrum of the surface image (after applying the filter) is to be shown in figures 7.9 and 7.10. It can be clearly seen from these figures that as surface roughness ‘Ra’ decreases, amplitude of power spectra is also decreased.

Power spectrum is a magnitude of Fourier transform of an image. As the surface becomes smoother i.e. roughness value decreases, then the amplitude of power spectrum also decreases. Figure 7.10 shows that amplitude of power spectrum of graphite specimen having roughness Ra = 4.8 µm is $5.5 \times 10^{-10}$ while as shown in figure 7.9, the amplitude of power spectrum of graphite specimen having roughness Ra = 1.8267 µm is $1.5 \times 10^{-10}$.

7.5.2.3 Evaluation of Optical Roughness Parameter

With the help of image processing tool of MATLAB software, the optical roughness arithmetic average of gray level, (Ga) is calculated using equations 5.4 and 5.5, for all the surfaces after capturing the images of surfaces.

Arithmetic average of the gray level ‘Ga’ (optical roughness) can be expressed as

$$Ga = \frac{\sum (g_1 - g_m l + g_2 - g_m l + g_3 - g_m l + \ldots + g_n - g_m l)}{n} \quad (5.4)$$

Where $g_1, g_2, g_3, \ldots, g_n$ are the gray level values of a surface of image along one line and $g_m$ is the mean of the gray values and this can be determined as

$$g_m = \frac{\sum (g_1 + g_2 + g_3 + \ldots + g_n)}{n} \quad (5.5)$$

After applying the low pass Gaussian filter to all images, again ‘Gaf’ is calculated. Finally ‘Ga’ values before applying filter and ‘Gaf’ values after applying the filter are compared with the respective ‘Ra’ values measured using a stylus instrument. To obtain the stylus roughness, ‘Ra’, the diamond stylus tip is moved over the machined surface of each specimen. Cut-off length is taken as 0.25 mm and total traverse length is 1.25 mm. Result of all calculated values ‘Ga’, ‘Gaf’ and measured ‘Ra’ for graphite specimens is shown in table 7.2.
TABLE 7.2
MACHINING PARAMETERS USED AND THE CORRESPONDING OPTICAL AND STYLUS ROUGHNESS VALUES FOR GRAPHITE SPECIMEN HAVING DENSITY 1.7136 g / cc

<table>
<thead>
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<th>S no</th>
<th>Speed (rpm)</th>
<th>Feed (mm/min)</th>
<th>$G_a$ (without Filter)</th>
<th>$G_{af}$ (with filter)</th>
<th>$R_a$ (μm)</th>
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</thead>
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7.5.2.4 Estimation of Correlation between Optical Roughness Parameters and Stylus Roughness Parameter

After calculating all the values of optical parameters ‘$G_a$’, before applying the filter to the images and ‘$G_{af}$’, after applying the filter to the images, the correlation is found out with surface roughness, ‘$R_a$’, measured with stylus instrument. To achieve this purpose the graph is drawn between the optical surface roughnesses ‘$G_a$’ (before applying the filter to the images) and stylus surface roughness, ‘$R_a$’ for the graphite specimen (density 1.7136 g / cc) which is shown in figure 7.11. Another graph is drawn between the optical surface roughness, ‘$G_{af}$’ (after applying the filter to the images) and stylus surface roughness, ‘$R_a$’ for the same graphite specimen which is shown in figure 7.12.

Figure 7.11 shows that there is a good cubic correlation established between optical roughness parameter ‘$G_a$’ (before applying filter) and stylus roughness ‘$R_a$’ for graphite specimen having density 1.7136 g / cc. The relationship between ‘$G_a$’ and ‘$R_a$’ for graphite specimen having density 1.7136 g / cc is

$$G_a = -4.368 \times R_a^3 + 40.5 \times R_a^2 - 110.7 \times R_a + 103.5 \quad (7.1)$$

Figure 7.12 shows that there is a better cubic correlation established between optical roughness parameter ‘$G_{af}$’ (after applying filter) and stylus roughness ‘$R_a$’ for graphite
Figure 7.9 3D Power spectrum of graphite (density = 1.7136 g/cc) having Ra = 1.8267 µm

Figure 7.10 3D Power spectrum of graphite (density = 1.7136 g/cc) having Ra = 4.8 µm

Figure 7.11 Correlation between stylus Ra and optical roughness Ga for graphite (density = 1.7136 g/cc)

Figure 7.12 Correlation between stylus Ra and optical roughness Gaf for graphite (density = 1.7136 g/cc)
specimen having density 1.7136 g/cc. Noise is reduced by applying filter to the images hence better correlation is established. The relationship between ‘Gaf’ and ‘Ra’ for graphite specimen having density 1.7136 g/cc is

\[
Gaf = -4.42 \times Ra^3 + 40.94 \times Ra^2 - 111.8 \times Ra + 103.1 \quad (7.2)
\]

### 7.5.3 Conclusions

The result obtained confirmed that the histogram and power spectrum can be successfully applied to decide whether the analyzed surface is coarse or smooth. Hence acceptance or rejection policy of the components can be generated by that. As the surface becomes smoother, reflectivity increases resulting into increase in the frequency of larger value intensity of histogram. There is a higher value of amplitude of power spectrum as surface having higher value of roughness i.e. rough surface. As surface becomes smooth, the amplitude of power spectrum decreases.

It is established that there is a good cubic correlation between stylus parameter ‘Ra’ and optical parameter ‘Ga’. The correlation of ‘Gaf’, optical parameter after applying the Gaussian filter has a better cubic correlation with the average surface roughness ‘Ra’ measured using a conventional and widely accepted stylus type instrument for the graphite specimen having density 1.7136 g/cc. After applying the filter, noise can be removed, which results in better cubic correlation between stylus roughness ‘Ra’ and optical roughness ‘Gaf’ for the graphite specimen having density 1.7136 g/cc. The governing equations are

\[
Ga = -4.368 \times Ra^3 + 40.5 \times Ra^2 - 110.7 \times Ra + 103.5 \quad (7.1)
\]

\[
Gaf = -4.42 \times Ra^3 + 40.94 \times Ra^2 - 111.8 \times Ra + 103.1 \quad (7.2)
\]
7.6 Experiments Carried out on Graphite Specimen having Density 1.999 g / cc

7.6.1 Experimental Procedure

Graphite specimen having density 1.999 g / cc is machined on vertical machining center (VMC-850) with 12mm, four fluted end mill. Various surface roughnesses are obtained by controlling the machining parameters i.e. different speeds and feeds on VMC machine.

According to the capability of VMC – 850 machine available and general recommendation of machining condition for graphite, the following parameters shown in table 7.3 are selected.

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<tr>
<td>6</td>
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</table>

The depth of cut of machining is set at 1mm. The images of these machined specimens are grabbed by high resolution color CCD camera (Samsung SDC-313B) having effective pixels 768 (H) x 494 (V) with binocular stereo microscope (RSM 4).

Low pass filter is applied to all images and histogram analysis and evaluation of optical surface roughness are done. Power spectrum is also obtained. These analyses are done with the help of image processing tool of Matlab. After completing the mentioned analysis, the arithmetic average roughness parameter is obtained for all specimens with the help of stylus roughness tester. Correlation is found out between measured stylus parameter and optical parameter.
7.6.2 Analysis of Result and Discussion

Analysis of each image is carried out. Here the images of graphite specimen (density 1.999 g/cc) having stylus roughness, ‘Ra’ of 2.85 μm and 4.44 μm are shown in figures 7.13 and 7.14.

7.6.2.1 Histogram Analysis

Gray scale analysis technique has been used for surface characteristic which is known as histogram. Histogram drawn shows the variation of grey level intensity as per the surface roughness of the surface. It shows the occurrence (frequency) of grey level intensity over the surface. Figures 7.15 and 7.16 show histograms of images having different surface roughness.

As the surface becomes smoother, there is an increase in the frequency of larger value intensity. In histogram, left side shows the smaller value of intensities and right side shows the larger value of intensities. As surface becomes smooth, reflectivity increases, resulting in higher value of frequencies for larger gray value intensities. In figure 7.16, rougher surface having surface roughness Ra = 4.44 μm, there is a dominance of gray levels 125 approximately having frequency (number of times each gray value occurs in image) 7000. However in the case of relatively smoother surface having surface roughness Ra = 2.85 μm, it is observed from figure 7.15 that 125 value of gray levels are having 10,000 frequency.

So from histogram one can judge that whether the surface is relatively smooth or rough. Histograms have the limitation that they carry no information regarding the relative position of the pixel intensities with respect to each other.
Figure 7.13 Image of graphite (density = 1.999 g/cc) having Ra = 2.85 μm

Figure 7.14 Image of graphite (density = 1.999 g/cc) having Ra = 4.44 μm

Figure 7.15 Histogram of graphite (density = 1.999 g/cc) having Ra = 2.85 μm

Figure 7.16 Histogram of graphite (density = 1.999 g/cc) having Ra = 4.44 μm
7.6.2.2 Fourier Analysis (Power Spectrum)

The 3-D perspective of the power spectrum of the surface image (after applying the filter) is to be shown in figures 7.17 and 7.18. It can be clearly seen from these figures that as surface roughness ‘Ra’ decreases, amplitude of power spectra is also decreased.

Power spectrum is a magnitude of Fourier transform of an image. As the surface becomes smoother i.e. roughness value decreases, then the amplitude of power spectrum also decreases. Figure 7.18 shows that amplitude of power spectrum of graphite specimen having roughness Ra = 4.44 μm is $3.5 \times 10^{10}$ while as shown in figure 7.17, the amplitude of power spectrum of graphite specimen having roughness Ra = 2.85 μm is $2 \times 10^{10}$.

7.6.2.3 Evaluation of Optical Roughness Parameter

With the help of image processing tool of MATLAB software, the optical roughness arithmetic average of gray level, (Ga) is calculated using equations 5.4 and 5.5, for all the surfaces after capturing the images of surfaces.

Arithmetic average of the gray level Ga (optical roughness) can be expressed as

$$Ga = \frac{\sum (g_1 - g_m + g_2 - g_m + g_3 - g_m + \ldots + g_n - g_m)}{n}$$  \hspace{1cm} (5.4)

Where $g_1, g_2, g_3, \ldots, g_n$ are the gray level values of a surface of image along one line and $g_m$ is the mean of the gray values and this can be determined as

$$g_m = \frac{\sum (g_1 + g_2 + g_3 + \ldots + g_n)}{n}$$  \hspace{1cm} (5.5)

After applying the low pass Gaussian filter to all images, again ‘Gaf’ is calculated. Finally ‘Ga’ values before applying filter and ‘Gaf’ values after applying the filter are compared with the respective ‘Ra’ values measured using a stylus instrument. To obtain the stylus roughness, ‘Ra’, the diamond stylus tip is moved over the machined surface of each specimen. Cut – off length is taken as 0.25 mm and total traverse length is 1.25 mm. Result of all calculated values ‘Ga’, ‘Gaf’ and measured ‘Ra’ for graphite specimens is shown in table 7.4.
TABLE 7.4
MACHINING PARAMETERS USED AND THE CORRESPONDING OPTICAL AND STYLUS ROUGHNESS VALUES FOR GRAPHITE SPECIMEN HAVING DENSITY 1.999 g / cc

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<th>S no</th>
<th>Speed (rpm)</th>
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<th>$G_{af}$ (with filter)</th>
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7.6.2.4 Estimation of Correlation between Optical Roughness Parameters and Stylus Roughness Parameter

After calculating all the values of optical parameters ‘Ga’, before applying the filter to the images and ‘Gaf’, after applying the filter to the images, the correlation is found out with surface roughness, ‘$R_a$’, measured with stylus instrument. To achieve this purpose the graph is drawn between the optical surface roughnesses $G_a$ (before applying the filter to the images) and stylus surface roughness, ‘$R_a$’ for the graphite specimen (density 1.999 g / cc) which is shown in figure 7.19. Another graph is drawn between the optical surface roughnesses, $G_{af}$ (after applying the filter to the images) and stylus surface roughness, ‘$R_a$’ for the same graphite specimen which is shown in figure 7.20.

Figure 7.19 shows that there is a good cubic correlation established between optical roughness parameter $G_a$ (before applying filter) and stylus roughness ‘$R_a$’ for graphite specimen having density 1.999 g / cc. The relationship between ‘$G_a$’ and ‘$R_a$’ for graphite specimen having density 1.999 g / cc is

$$G_a = -19.14 \times R_a^3 + 203.4 \times R_a^2 - 704 \times R_a + 810.7 \quad (7.3)$$
Figure 7.17 3D Power spectrum of graphite (density = 1.999 g/cc) having Ra = 2.85 μm

Figure 7.18 3D Power spectrum of graphite (density = 1.999 g/cc) having Ra = 4.44 μm

Figure 7.19 Correlation between stylus Ra and optical roughness Ga for graphite (density = 1.999 g/cc)

Figure 7.20 Correlation between stylus Ra and optical roughness Ga for graphite (density = 1.999 g/cc)
Figure 7.20 shows that there is a better cubic correlation established between optical roughness parameter Gaf (after applying filter) and stylus roughness ‘Ra’ for graphite specimen having density 1.999 g / cc. Noise is reduced by applying filter to the images hence better correlation is established. The relationship between ‘Gaf’ and ‘Ra’ for graphite specimen having density 1.999 g / cc is

\[ Gaf = -18.88 \times Ra^3 + 200.5 \times Ra^2 - 693.1 \times Ra + 796 \] (7.4)

7.6.3 Conclusions

The result obtained confirmed that the histogram and power spectrum can be successfully applied to decide whether the analyzed surface is coarse or smooth. Hence acceptance or rejection policy of the components can be generated by that. As the surface becomes smoother, reflectivity increases resulting into increase in the frequency of larger value intensity of histogram. There is a higher value of amplitude of power spectrum as surface having higher value of roughness i.e. rough surface. As surface becomes smooth, the amplitude of power spectrum decreases.

It is established that there is a good cubic correlation between stylus parameter ‘Ra’ and optical parameter ‘Ga’. The correlation of ‘Gaf’, optical parameter after applying the Gaussian filter has a better cubic correlation with the average surface roughness ‘Ra’ measured using a conventional and widely accepted stylus type instrument for the graphite specimen having density 1.999 g / cc. After applying the filter, noise can be removed, which results in better cubic correlation between stylus roughness ‘Ra’ and optical roughness ‘Gaf’ for the graphite specimen having density 1.999 g / cc. The governing equations are

\[ Ga = -19.14 \times Ra^3 + 203.4 \times Ra^2 - 704 \times Ra + 810.7 \] (7.3)

\[ Gaf = -18.88 \times Ra^3 + 200.5 \times Ra^2 - 693.1 \times Ra + 796 \] (7.4)
7.7 Experiments Carried out on Graphite Specimen having Density 1.705571 g / cc

7.7.1 Experimental Procedure

Graphite specimen having density 1.705571 g / cc is machined on vertical machining center (VMC-850) with 12mm, four fluted end mill. Various surface roughnesses are obtained by controlling the machining parameters i.e. different speeds and feeds on VMC machine.

According to the capability of VMC – 850 machine available and general recommendation of machining condition for graphite, the following parameters shown in table 7.5 are selected.

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The depth of cut of machining is set at 1mm. The images of these machined specimens are grabbed by high resolution color CCD camera (Samsung SDC-313B) having effective pixels 768 (H) x 494 (V) with binocular stereo microscope (RSM 4).

Low pass filter is applied to all images. Histogram analysis and evaluation of optical surface roughness are carried out. Power spectrum is also obtained. These analyses are done with the help of image processing tool of Matlab. After completing the mentioned analysis, the arithmetic average roughness parameter is obtained for all specimens with the help of
stylus roughness tester. Correlation is found out between measured stylus parameter and optical parameter.

### 7.7.2 Analysis of Result and Discussion

Analysis of each image is carried out. Here the images of graphite specimen (density 1.705571 g / cc) having stylus roughness, ‘Ra’ of 1.5133 μm and 3.45666 μm are shown in figures 7.21 and 7.22.

#### 7.7.2.1 Histogram Analysis

Gray scale analysis technique has been used for surface characteristic which is known as histogram. Histogram drawn shows the variation of grey level intensity as per the surface roughness of the surface. It shows the occurrence (frequency) of grey level intensity over the surface. Figures 7.23 and 7.24 show histograms of images having different surface roughness.

As the surface becomes smoother, there is an increase in the frequency of larger value intensity. In histogram, left side shows the smaller value of intensities and right side shows the larger value of intensities. As surface becomes smooth, reflectivity increases, resulting in higher value of frequencies for larger gray value intensities. In figure 7.24, rougher surface having surface roughness Ra = 3.45666 μm, there is a dominance of gray levels 125 approximately having frequency (number of times each gray value occurs in image) 6500. However in the case of relatively smoother surface having surface roughness Ra = 1.5133 μm, it is observed from figure 7.23 that 125 value of gray level is having 10,000 frequency.

So from histogram one can judge that whether the surface is relatively smooth or rough. Histograms have the limitation that they carry no information regarding the relative position of the pixel intensities with respect to each other.
Figure 7.21 Image of graphite (density = 1.705571 g/cc) having Ra = 1.5133 μm

Figure 7.22 Image of graphite (density = 1.705571 g/cc) having Ra = 3.45666 μm

Figure 7.23 Histogram of graphite (density = 1.705571 g/cc) having Ra = 1.5133 μm

Figure 7.24 Histogram of graphite (density = 1.705571 g/cc) having Ra = 3.45666 μm
7.7.2.2 Fourier Analysis (Power Spectrum)

The 3-D perspective of the power spectrum of the surface image (after applying the filter) is to be shown in figures 7.25 and 7.26. It can be clearly seen from these figures that as surface roughness ‘Ra’ decreases, amplitude of power spectra is also decreased.

Power spectrum is a magnitude of Fourier transform of an image. As the surface becomes smoother i.e. roughness value decreases, then the amplitude of power spectrum also decreases. Figure 7.26 shows that amplitude of power spectrum of graphite specimen having roughness Ra = 3.45666 μm is $3 \times 10^{10}$ while as shown in figure 7.25, the amplitude of power spectrum of graphite specimen having roughness Ra = 1.5133 μm is $1.9 \times 10^{10}$.

7.7.2.3 Evaluation of Optical Roughness Parameter

With the help of image processing tool of MATLAB software, the optical roughness arithmetic average of gray level, (Ga) is calculated using equations 5.4 and 5.5, for all the surfaces after capturing the images of surfaces.

Arithmetic average of the gray level Ga (optical roughness) can be expressed as

$$Ga = \frac{\left( \Sigma (1g_1 - g_m + 1g_2 - g_m + 1g_3 - g_m + \ldots + 1g_n - g_m) \right)}{n}$$  \hspace{1cm} (5.4)

Where $g_1, g_2, g_3, \ldots, g_n$ are the gray level values of a surface of image along one line and $g_m$ is the mean of the gray values and this can be determined as

$$g_m = \frac{\left( \Sigma (g_1 + g_2 + g_3 + \ldots + g_n) \right)}{n}$$  \hspace{1cm} (5.5)

After applying the low pass Gaussian filter to all images, again ‘Gaf’ is calculated. Finally ‘Ga’ values before applying filter and ‘Gaf’ values after applying the filter are compared with the respective ‘Ra’ values measured using a stylus instrument. To obtain the stylus roughness, ‘Ra’, the diamond stylus tip is moved over the machined surface of each specimen. Cut-off length is taken as 0.25 mm and total traverse length is 1.25 mm. Result of all calculated values ‘Ga’, ‘Gaf’ and measured ‘Ra’ for graphite specimens is shown in table 7.6.
TABLE 7.6
MACHINING PARAMETERS USED AND THE CORRESPONDING OPTICAL AND STYLUS ROUGHNESS VALUES FOR GRAPHITE SPECIMEN HAVING DENSITY 1.705571 g / cc

<table>
<thead>
<tr>
<th>S no</th>
<th>Speed (rpm)</th>
<th>Feed (mm/min)</th>
<th>G_a (without filter)</th>
<th>G_af (with filter)</th>
<th>R_a (µm)</th>
</tr>
</thead>
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<td>11.97847</td>
<td>10.688533</td>
<td>1.5133</td>
</tr>
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<td>50</td>
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<td>1.782</td>
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<tr>
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<td>50</td>
<td>12.27931667</td>
<td>11.08156667</td>
<td>2.44</td>
</tr>
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<td>1000</td>
<td>50</td>
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<td>15.63925</td>
<td>2.7625</td>
</tr>
<tr>
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<td>17.9697333</td>
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<td>3.45666</td>
</tr>
</tbody>
</table>

7.7.2.4 Estimation of Correlation between Optical Roughness Parameters and Stylus Roughness Parameter

After calculating all the values of optical parameters ‘G_a’, before applying the filter to the images and ‘G_af’, after applying the filter to the images, the correlation is found out with surface roughness, ‘R_a’, measured with stylus instrument. To achieve this purpose the graph is drawn between the optical surface roughnesses G_a (before applying the filter to the images) and stylus surface roughness, ‘R_a’ for the graphite specimen (density 1.705571 g / cc) which is shown in figure 7.27. Another graph is drawn between the optical surface roughnesses, Gaf (after applying the filter to the images) and stylus surface roughness, ‘R_a’ for the same graphite specimen which is shown in figure 7.28.

Figure 7.27 shows that there is a good cubic correlation established between optical roughness parameter G_a (before applying filter) and stylus roughness ‘R_a’ for graphite specimen having density 1.705571 g / cc. The relationship between ‘G_a’ and ‘R_a’ for graphite specimen having density 1.705571 g / cc is

\[ G_a = 2.341 \times R_a^3 - 15.32 \times R_a^2 + 33.53 \times R_a - 11.43 \]  

(7.5)
Figure 7.25 3D Power spectrum of graphite (density = 1.705571 g/cc) having $Ra = 1.5133 \, \mu m$

Figure 7.26 3D Power spectrum of graphite (density = 1.705571 g/cc) having $Ra = 3.45666 \, \mu m$

Figure 7.27 Correlation between stylus $Ra$ and optical roughness $Ga$ for graphite (density = 1.70551 g/cc)

Figure 7.28 Correlation between stylus $Ra$ and optical roughness $Gaf$ for graphite (density = 1.705571 g/cc)
Figure 7.28 shows that there is a better cubic correlation established between optical roughness parameter $G_{af}$ (after applying filter) and stylus roughness ‘$Ra$’ for graphite specimen having density $1.705571 \text{ g/cc}$. Noise is reduced by applying filter to the images hence better correlation is established. The relationship between ‘$G_{af}$’ and ‘$Ra$’ for graphite specimen having density $1.705571 \text{ g/cc}$ is

$$G_{af} = 2.416 \times Ra^3 - 15.91 \times Ra^2 + 35.01 \times Ra - 13.84 \quad (7.6)$$

### 7.7.3 Conclusions

The result obtained confirmed that the histogram and power spectrum can be successfully applied to decide whether the analyzed surface is coarse or smooth. Hence acceptance or rejection policy of the components can be generated by that. As the surface becomes smoother, reflectivity increases resulting into increase in the frequency of larger value intensity of histogram. There is a higher value of amplitude of power spectrum as surface having higher value of roughness i.e. rough surface. As surface becomes smooth, the amplitude of power spectrum decreases.

It is established that there is a good cubic correlation between stylus parameter ‘$Ra$’ and optical parameter ‘$Ga$’. The correlation of ‘$G_{af}$’, optical parameter after applying the Gaussian filter has a better cubic correlation with the average surface roughness ‘$Ra$’ measured using a conventional and widely accepted stylus type instrument for the graphite specimen having density $1.705571 \text{ g/cc}$. After applying the filter, noise can be removed, which results in better cubic correlation between stylus roughness ‘$Ra$’ and optical roughness ‘$G_{af}$’ for the graphite specimen having density $1.705571 \text{ g/cc}$. The governing equations are

$$Ga = 2.341 \times Ra^3 - 15.32 \times Ra^2 + 33.53 \times Ra - 11.43 \quad (7.5)$$

$$G_{af} = 2.416 \times Ra^3 - 15.91 \times Ra^2 + 35.01 \times Ra - 13.84 \quad (7.6)$$
7.8 Experiments Carried out on Graphite Specimen having Density 1.643197 g / cc

7.8.1 Experimental Procedure

Graphite specimen having density 1.643197 g / cc is machined on vertical machining center (VMC-850) with 12mm, four fluted end mill. Various surface roughnesses are obtained by controlling the machining parameters i.e. different speeds and feeds on VMC machine.

According to the capability of VMC - 850 machine available and general recommendation of machining condition for graphite, the following parameters shown in table 7.7 are selected.

<table>
<thead>
<tr>
<th>S no</th>
<th>Speed (rpm)</th>
<th>Feed (mm/min)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
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</tr>
<tr>
<td>2</td>
<td>4500</td>
<td>50</td>
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<tr>
<td>3</td>
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<tr>
<td>4</td>
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<tr>
<td>8</td>
<td>1000</td>
<td>300</td>
</tr>
</tbody>
</table>

The depth of cut of machining is set at 1mm. The images of these machined specimens are grabbed by high resolution color CCD camera (Samsung SDC-313B) having effective pixels 768 (H) x 494 (V) with binocular stereo microscope (RSM 4).

Low pass filter is applied to all images. Histogram analysis and evaluation of optical surface roughness are carried out. Power spectrum is also obtained. These analyses are done with the help of image processing tool of Matlab. After completing the mentioned analysis, the arithmetic average roughness parameter is obtained for all specimens with the help of
stylus roughness tester. Correlation is found out between measured stylus parameter and optical parameter.

### 7.8.2 Analysis of Result and Discussion

Analysis of each image is carried out. Here the images of graphite specimen (density 1.643197 g / cc) having stylus roughness, ‘Ra’ of 5.016 μm and 6.6933 μm are shown in figures 7.29 and 7.30.

#### 7.8.2.1 Histogram Analysis

Gray scale analysis technique has been used for surface characteristic which is known as histogram. Histogram drawn shows the variation of grey level intensity as per the surface roughness of the surface. It shows the occurrence (frequency) of grey level intensity over the surface. Figures 7.31 and 7.32 show histograms of images having different surface roughness.

As the surface becomes smoother, there is an increase in the frequency of larger value intensity. In histogram, left side shows the smaller value of intensities and right side shows the larger value of intensities. As surface becomes smooth, reflectivity increases, resulting in higher value of frequencies for larger gray value intensities. In figure 7.32, rougher surface having surface roughness Ra = 6.6933 μm, there is a dominance of gray level 125 approximately having frequency (number of times each gray value occurs in image) 6000. However in the case of relatively smoother surface having surface roughness Ra = 5.016 μm, it is observed from figure 7.31 that 125 value of gray level is having 7000 frequency.

So from histogram one can judge that whether the surface is relatively smooth or rough. Histograms have the limitation that they carry no information regarding the relative position of the pixel intensities with respect to each other.
Figure 7.29 Image of graphite 
(density = 1.643197 g/cc) 
having Ra = 5.016 μm

Figure 7.30 Image of graphite 
(density = 1.643197 g/cc) 
having Ra = 6.6933 μm

Figure 7.31 Histogram of graphite 
(density = 1.643197 g/cc) 
having Ra = 5.016 μm

Figure 7.32 Histogram of graphite 
(density = 1.643197 g/cc) 
having Ra = 6.6933 μm
7.8.2.2 Fourier Analysis (Power Spectrum)

The 3-D perspective of the power spectrum of the surface image (after applying the filter) is to be shown in figures 7.33 and 7.34. It can be clearly seen from these figures that as surface roughness ‘Ra’ decreases, amplitude of power spectra is also decreased.

Power spectrum is a magnitude of Fourier transform of an image. As the surface becomes smoother i.e. roughness value decreases, then the amplitude of power spectrum also decreases. Figure 7.34 shows that amplitude of power spectrum of graphite specimen having roughness Ra = 6.6933 μm is $2.75 \times 10^{-10}$ while as shown in figure 7.33, the amplitude of power spectrum of graphite specimen having roughness Ra = 5.016 μm is $1.98 \times 10^{-10}$.

7.8.2.3 Evaluation of Optical Roughness Parameter

With the help of image processing tool of MATLAB software, the optical roughness arithmetic average of gray level, (Ga) is calculated using equations 5.4 and 5.5, for all the surfaces after capturing the images of surfaces.

Arithmetic average of the gray level Ga (optical roughness) can be expressed as

$$Ga = \frac{\sum (g_1 - g_m) + (g_2 - g_m) + (g_3 - g_m) + \ldots \ldots + (g_n - g_m))}{n} \quad (5.4)$$

Where $g_1, g_2, g_3, \ldots, g_n$ are the gray level values of a surface of image along one line and $g_m$ is the mean of the gray values and this can be determined as

$$g_m = \frac{\sum (g_1 + g_2 + g_3 + \ldots + g_n)}{n} \quad (5.5)$$

After applying the low pass Gaussian filter to all images, again ‘Gaf’ is calculated. Finally ‘Ga’ values before applying filter and ‘Gaf’ values after applying the filter are compared with the respective ‘Ra’ values measured using a stylus instrument. To obtain the stylus roughness, ‘Ra’, the diamond stylus tip is moved over the machined surface of each specimen. Cut-off length is taken as 0.25 mm and total traverse length is 1.25 mm. Result of all calculated values ‘Ga’, ‘Gaf’ and measured ‘Ra’ for graphite specimens is shown in table 7.6.
### TABLE 7.8
MACHINING PARAMETERS USED AND THE CORRESPONDING OPTICAL AND STYLUS ROUGHNESS VALUES FOR GRAPHITE SPECIMEN HAVING DENSITY 1.643197 g / cc

<table>
<thead>
<tr>
<th>S no</th>
<th>Speed (rpm)</th>
<th>Feed (mm/min)</th>
<th>$G_a$ (without filter)</th>
<th>$G_{af}$ (with filter)</th>
<th>$R_a$ (µm)</th>
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</thead>
<tbody>
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<td>1</td>
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<td>18.417333</td>
<td>17.2194333</td>
<td>6.47285</td>
</tr>
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<td>7.035</td>
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<td>7.496</td>
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<td>1000</td>
<td>300</td>
<td>20.85026</td>
<td>19.67875</td>
<td>5.6933</td>
</tr>
</tbody>
</table>

### 7.8.2.4 Estimation of Correlation between Optical Roughness Parameters and Stylus Roughness Parameter

After calculating all the values of optical parameters ‘$G_a$’, before applying the filter to the images and ‘$G_{af}$’, after applying the filter to the images, the correlation is found out with surface roughness, ‘$R_a$’, measured with stylus instrument. To achieve this purpose the graph is drawn between the optical surface roughness $G_a$ (before applying the filter to the images) and stylus surface roughness, ‘$R_a$’ for the graphite specimen (density 1.643197 g / cc) which is shown in figure 7.35. Another graph is drawn between the optical surface roughness, $G_{af}$ (after applying the filter to the images) and stylus surface roughness, ‘$R_a$’ for the same graphite specimen which is shown in figure 7.36.

Figure 7.35 shows that there is a good cubic correlation established between optical roughness parameter $G_a$ (before applying filter) and stylus roughness ‘$R_a$’ for graphite specimen having density 1.643197 g / cc. The relationship between ‘$G_a$’ and ‘$R_a$’ for graphite specimen having density 1.643197 g / cc is

$$G_a = -0.4442 \times R_a^3 + 7.044 \times R_a^2 - 35.17 \times R_a + 72.93 \tag{7.7}$$
Figure 7.33 3D Power spectrum of graphite (density = 1.643197 g/cc) having Ra = 5.016 μm

Figure 7.34 3D Power spectrum of graphite (density = 1.643197 g/cc) having Ra = 6.6933 μm

Figure 7.35 Correlation between stylus Ra and optical roughness Ga for graphite (density = 1.643197 g/cc)

Figure 7.36 Correlation between stylus Ra and optical roughness Gaf for graphite (density = 1.643197 g/cc)
Figure 7.36 shows that there is a better cubic correlation established between optical roughness parameter $G_{af}$ (after applying filter) and stylus roughness $'Ra'$ for graphite specimen having density 1.643197 g / cc. Noise is reduced by applying filter to the images hence better correlation is established. The relationship between $'G_{af}$' and $'Ra'$ for graphite specimen having density 1.643197 g / cc is

$$G_{af} = -0.4137 \times Ra^3 + 6.504 \times Ra^2 - 31.99 \times Ra + 65.6$$  \hspace{1cm} (7.8)

7.8.3 Conclusions

The result obtained confirmed that the histogram and power spectrum can be successfully applied to decide whether the analyzed surface is coarse or smooth. Hence acceptance or rejection policy of the components can be generated by that. As the surface becomes smoother, reflectivity increases resulting into increase in the frequency of larger value intensity of histogram. There is a higher value of amplitude of power spectrum as surface having higher value of roughness i.e. rough surface. As surface becomes smooth, the amplitude of power spectrum decreases.

It is established that there is a good cubic correlation between stylus parameter $'Ra'$ and optical parameter $'G_{af}'$. The correlation of $'G_{af}'$, optical parameter after applying the Gaussian filter has a better cubic correlation with the average surface roughness $'Ra'$ measured using a conventional and widely accepted stylus type instrument for the graphite specimen having density 1.643197 g / cc. After applying the filter, noise can be removed, which results in better cubic correlation between stylus roughness $'Ra'$ and optical roughness $'G_{af}'$ for the graphite specimen having density 1.643197 g / cc. The governing equations are

$$Ga = -0.4442 \times Ra^3 + 7.044 \times Ra^2 - 35.17 \times Ra + 72.93$$  \hspace{1cm} (7.7)

$$G_{af} = -0.4137 \times Ra^3 + 6.504 \times Ra^2 - 31.99 \times Ra + 65.6$$  \hspace{1cm} (7.8)
7.9 Experiments Carried out on Graphite Specimen having Density 1.630556 g / cc

7.9.1 Experimental Procedure

Graphite specimen having density 1.630556 g / cc is machined on vertical machining center (VMC-850) with 12mm, four fluted end mill. Various surface roughnesses are obtained by controlling the machining parameters i.e. different speeds and feeds on VMC machine.

According to the capability of VMC – 850 machine available and general recommendation of machining condition for graphite, the following parameters shown in table 7.9 are selected.

<table>
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<tr>
<th>S no</th>
<th>Speed (rpm)</th>
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The depth of cut of machining is set at 1mm. The images of these machined specimens are grabbed by high resolution color CCD camera (Samsung SDC-313B) having effective pixels 768 (H) x 494 (V) with binocular stereo microscope (RSM 4).

Low pass filter is applied to all images. Histogram analysis and evaluation of optical surface roughness are carried out. Power spectrum is also obtained. These analyses are done with the help of image processing tool of Matlab. After completing the mentioned analysis, the arithmetic average roughness parameter is obtained for all specimens with the help of
stylus roughness tester. Correlation is found out between measured stylus parameter and optical parameter.

7.9.2 Analysis of Result and Discussion

Analysis of each image is carried out. Here the images of graphite specimen (density 1.630556 g / cc) having stylus roughness, ‘Ra’ of 2.04 μm and 2.9933 μm are shown in figures 7.37 and 7.38.

7.9.2.1 Histogram Analysis

Gray scale analysis technique has been used for surface characteristic which is known as histogram. Histogram drawn shows the variation of grey level intensity as per the surface roughness of the surface. It shows the occurrence (frequency) of grey level intensity over the surface. Figures 7.39 and 7.40 show histograms of images having different surface roughness.

As the surface becomes smoother, there is an increase in the frequency of larger value intensity. In histogram, left side shows the smaller value of intensities and right side shows the larger value of intensities. As surface becomes smooth, reflectivity increases, resulting in higher value of frequencies for larger gray value intensities. In figure 7.40, rougher surface having surface roughness Ra = 2.9933 μm, there is a dominance of gray level 150 approximately having frequency (number of times each gray value occurs in image) 4000. As well as rougher surface has non uniform histogram compared to smoother surface. However in the case of relatively smoother surface having surface roughness Ra = 2.04μm, it is observed from figure 7.39 that 150 value of gray level is having 6000 frequency.

So from histogram one can judge that whether the surface is relatively smooth or rough. Histograms have the limitation that they carry no information regarding the relative position of the pixel intensities with respect to each other.
Figure 7.37 Image of graphite (density = 1.630556 g/cc) having $Ra = 2.04 \mu m$

Figure 7.38 Image of graphite (density = 1.630556 g/cc) having $Ra = 2.9933 \mu m$

Figure 7.39 Histogram of graphite (density = 1.630556 g/cc) having $Ra = 2.04 \mu m$

Figure 7.40 Histogram of graphite (density = 1.630556 g/cc) having $Ra = 2.9933 \mu m$
7.9.2.2 Fourier Analysis (Power Spectrum)

The 3-D perspective of the power spectrum of the surface image (after applying the filter) is to be shown in figures 7.41 and 7.42. It can be clearly seen from these figures that as surface roughness ‘Ra’ decreases, amplitude of power spectra is also decreased.

Power spectrum is a magnitude of Fourier transform of an image. As the surface becomes smoother i.e. roughness value decreases, then the amplitude of power spectrum also decreases. Figure 7.42 shows that amplitude of power spectrum of graphite specimen having roughness Ra = 2.9933 μm is $4.5 \times 10^{10}$ while as shown in figure 7.41, the amplitude of power spectrum of graphite specimen having roughness Ra = 2.04 μm is $3.9 \times 10^{10}$.

7.9.2.3 Evaluation of Optical Roughness Parameter

With the help of image processing tool of MATLAB software, the optical roughness arithmetic average of gray level, (Ga) is calculated using equations 5.4 and 5.5, for all the surfaces after capturing the images of surfaces.

Arithmetic average of the gray level Ga (optical roughness) can be expressed as

$$Ga = \left( \frac{\Sigma (|g_1 - g_m| + |g_2 - g_m| + |g_3 - g_m| + \ldots + |g_n - g_m|)}{n} \right)$$  \hspace{1cm} (5.4)

Where $g_1, g_2, g_3, \ldots, g_n$ are the gray level values of a surface of image along one line and $g_m$ is the mean of the gray values and this can be determined as

$$g_m = \left( \frac{\Sigma (g_1 + g_2 + g_3 + \ldots + g_n)}{n} \right)$$  \hspace{1cm} (5.5)

After applying the low pass Gaussian filter to all images, again ‘Gaf’ is calculated. Finally ‘Ga’ values before applying filter and ‘Gaf’ values after applying the filter are compared with the respective ‘Ra’ values measured using a stylus instrument. To obtain the stylus roughness, ‘Ra’, the diamond stylus tip is moved over the machined surface of each specimen. Cut-off length is taken as 0.25 mm and total traverse length is 1.25 mm. Result of all calculated values ‘Ga’, ‘Gaf’ and measured ‘Ra’ for graphite specimens is shown in table 7.10.
TABLE 7.10
MACHINING PARAMETERS USED AND THE CORRESPONDING OPTICAL AND STYLUS ROUGHNESS VALUES FOR GRAPHITE SPECIMEN HAVING DENSITY 1.630556 g / cc

<table>
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<th>S no</th>
<th>Speed (rpm)</th>
<th>Feed (mm/min)</th>
<th>( G_a ) (without Filter)</th>
<th>( G_{af} ) (with filter)</th>
<th>( R_a ) (µm)</th>
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<td>21.9385</td>
<td>20.6717</td>
<td>1.6125</td>
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</tr>
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</tr>
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<td>7</td>
<td>1000</td>
<td>300</td>
<td>28.02197</td>
<td>26.541487</td>
<td>2.9933</td>
</tr>
</tbody>
</table>

7.9.2.4 Estimation of Correlation between Optical Roughness Parameters and Stylus Roughness Parameter

After calculating all the values of optical parameters ‘Ga’, before applying the filter to the images and ‘Gaf’, after applying the filter to the images, the correlation is found out with surface roughness, ‘Ra’, measured with stylus instrument. To achieve this purpose the graph is drawn between the optical surface roughness \( G_a \) (before applying the filter to the images) and stylus surface roughness, ‘Ra’ for the graphite specimen (density 1.630556 g / cc) which is shown in figure 7.43. Another graph is drawn between the optical surface roughnesses, \( G_{af} \) (after applying the filter to the images) and stylus surface roughness, ‘Ra’ for the same graphite specimen which is shown in figure 7.44.

Figure 7.43 shows that there is a good cubic correlation established between optical roughness parameter \( G_a \) (before applying filter) and stylus roughness ‘Ra’ for graphite specimen having density 1.630556 g / cc. The relationship between ‘Ga’ and ‘Ra’ for graphite specimen having density 1.630556 g / cc is

\[
G_a = 3.7 \times Ra^3 - 25 \times Ra^2 + 55 \times Ra - 18
\]  
(7.9)
Figure 7.41 3D Power spectrum of graphite (density = 1.6305567 g/cc) having Ra = 2.04 μm

Figure 7.42 3D Power spectrum of graphite (density = 1.6305567 g/cc) having Ra = 2.9933 μm

Figure 7.43 Correlation between stylus Ra and optical roughness Ga for graphite (density = 1.6305567 g/cc)

Figure 7.44 Correlation between stylus Ra and optical roughness Gaf for graphite (density = 1.6305567 g/cc)
Figure 7.44 shows that there is a better cubic correlation established between optical roughness parameter \( G_{af} \) (after applying filter) and stylus roughness ‘\( Ra \)’ for graphite specimen having density 1.630556 g / cc. Noise is reduced by applying filter to the images hence better correlation is established. The relationship between ‘\( G_{af} \)’ and ‘\( Ra \)’ for graphite specimen having density 1.630556 g / cc is

\[
G_{af} = 3.2 \times Ra^3 - 21 \times Ra^2 + 45 \times Ra - 11 \tag{7.10}
\]

7.9.3 Conclusions

The result obtained confirmed that the histogram and power spectrum can be successfully applied to decide whether the analyzed surface is coarse or smooth. Hence acceptance or rejection policy of the components can be generated by that. As the surface becomes smoother, reflectivity increases resulting into increase in the frequency of larger value intensity of histogram. There is a higher value of amplitude of power spectrum as surface having higher value of roughness i.e. rough surface. As surface becomes smooth, the amplitude of power spectrum decreases.

It is established that there is a good cubic correlation between stylus parameter ‘\( Ra \)’ and optical parameter ‘\( Ga \)’. The correlation of ‘\( G_{af} \)’, optical parameter after applying the Gaussian filter has a better cubic correlation with the average surface roughness ‘\( Ra \)’ measured using a conventional and widely accepted stylus type instrument for the graphite specimen having density 1.630556 g / cc. After applying the filter, noise can be removed, which results in better cubic correlation between stylus roughness ‘\( Ra \)’ and optical roughness ‘\( G_{af} \)’ for the graphite specimen having density 1.630556 g / cc. The governing equations are

\[
Ga = 3.7 \times Ra^3 - 25 \times Ra^2 + 55 \times Ra - 18 \tag{7.9}
\]

\[
G_{af} = 3.2 \times Ra^3 - 21 \times Ra^2 + 45 \times Ra - 11 \tag{7.10}
\]
7.10 Experiments Carried out on Graphite Specimen having Density 1.541 g / cc

7.10.1 Experimental Procedure

Graphite specimen having density 1.541 g / cc is machined on vertical machining center (VMC-850) with 12mm, four fluted end mill. Various surface roughnesses are obtained by controlling the machining parameters i.e. different speeds and feeds on VMC machine.

According to the capability of VMC – 850 machine available and general recommendation of machining condition for graphite, the following parameters shown in table 7.11 are selected.

<table>
<thead>
<tr>
<th>S no</th>
<th>Speed (rpm)</th>
<th>Feed (mm/min)</th>
</tr>
</thead>
<tbody>
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<td>50</td>
</tr>
<tr>
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<td>6000</td>
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<tr>
<td>5</td>
<td>3000</td>
<td>100</td>
</tr>
</tbody>
</table>

The depth of cut of machining is set at 2 mm. The images of these machined specimens are grabbed by high resolution color CCD camera (Samsung SDC-313B) having effective pixels 768 (H) x 494 (V) with binocular stereo microscope (RSM 4).

Low pass filter is applied to all images. Histogram analysis and evaluation of optical surface roughness are carried out. Power spectrum is also obtained. These analyses are done with the help of image processing tool of Matlab. After completing the mentioned analysis, the arithmetic average roughness parameter is obtained for all specimens with the help of stylus roughness tester. Correlation is found out between measured stylus parameter and optical parameter.
7.10.2 Analysis of Result and Discussion

Analysis of each image is carried out. Here the images of graphite specimen (density 1.541 g/cm³) having stylus roughness, ‘Ra’ of 1.69 μm and 3.8166 μm are shown in figures 7.45 and 7.46.

7.10.2.1 Histogram Analysis

Gray scale analysis technique has been used for surface characteristic which is known as histogram. Histogram drawn shows the variation of grey level intensity as per the surface roughness of the surface. It shows the occurrence (frequency) of grey level intensity over the surface. Figures 7.47 and 7.48 show histograms of images having different surface roughness.

As the surface becomes smoother, there is an increase in the frequency of larger value intensity. In histogram, left side shows the smaller value of intensities and right side shows the larger value of intensities. As surface becomes smooth, reflectivity increases, resulting in higher value of frequencies for larger gray value intensities. In figure 7.48, rougher surface having surface roughness Ra = 3.8166 μm, there is a dominance of gray level 100 approximately having frequency (number of times each gray value occurs in image) 12000. However in the case of relatively smoother surface having surface roughness Ra = 1.69 μm, it is observed from figure 7.47 that 100 value of gray level is having 14000 frequency.

So from histogram one can judge that whether the surface is relatively smooth or rough. Histograms have the limitation that they carry no information regarding the relative position of the pixel intensities with respect to each other.
Figure 7.45 Image of graphite (density = 1.541 g/cc) having Ra = 1.69 μm

Figure 7.46 Image of graphite (density = 1.541 g/cc) having Ra = 3.8166 μm

Figure 7.47 Histogram of graphite (density = 1.541 g/cc) having Ra = 1.69 μm

Figure 7.48 Histogram of graphite (density = 1.541 g/cc) having Ra = 3.8166 μm
7.10.2.2 Fourier Analysis (Power Spectrum)

The 3-D perspective of the power spectrum of the surface image (after applying the filter) is to be shown in figures 7.49 and 7.50. It can be clearly seen from these figures that as surface roughness ‘Ra’ decreases, amplitude of power spectra is also decreased.

Power spectrum is a magnitude of Fourier transform of an image. As the surface becomes smoother i.e. roughness value decreases, then the amplitude of power spectrum also decreases. Figure 7.50 shows that amplitude of power spectrum of graphite specimen having roughness Ra = 3.8166 μm is $1.1 \times 10^{10}$ while as shown in figure 7.49, the amplitude of power spectrum of graphite specimen having roughness Ra = 1.69 μm is $0.7 \times 10^{10}$.

7.10.2.3 Evaluation of Optical Roughness Parameter

With the help of image processing tool of MATLAB software, the optical roughness arithmetic average of gray level, (Ga) is calculated using equations 5.4 and 5.5, for all the surfaces after capturing the images of surfaces.

Arithmetic average of the gray level Ga (optical roughness) can be expressed as

$$Ga = \left( \frac{1}{n} \left( g_1 - g_m + g_2 - g_m + g_3 - g_m + \ldots + g_n - g_m \right) \right)$$

(5.4)

Where $g_1, g_2, g_3, \ldots, g_n$ are the gray level values of a surface of image along one line and $g_m$ is the mean of the gray values and this can be determined as

$$g_m = \left( \frac{1}{n} (g_1 + g_2 + g_3 + \ldots + g_n) \right)$$

(5.5)

After applying the low pass Gaussian filter to all images, again ‘Gaf’ is calculated. Finally ‘Ga’ values before applying filter and ‘Gaf’ values after applying the filter are compared with the respective ‘Ra’ values measured using a stylus instrument. To obtain the stylus roughness, ‘Ra’, the diamond stylus tip is moved over the machined surface of each specimen. Cut-off length is taken as 0.25 mm and total traverse length is 1.25 mm. Result of all calculated values ‘Ga’, ‘Gaf’ and measured ‘Ra’ for graphite specimens is shown in table 7.12.
TABLE 7.12
MACHINING PARAMETERS USED AND THE CORRESPONDING OPTICAL AND STYLUS ROUGHNESS VALUES FOR GRAPHITE SPECIMEN HAVING DENSITY 1.541 g / cc

<table>
<thead>
<tr>
<th>S no</th>
<th>Speed (rpm)</th>
<th>Feed (mm/min)</th>
<th>G&lt;sub&gt;a&lt;/sub&gt; (without filter)</th>
<th>G&lt;sub&gt;af&lt;/sub&gt; (with filter)</th>
<th>R&lt;sub&gt;a&lt;/sub&gt; (µm)</th>
</tr>
</thead>
<tbody>
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<td>7.9081</td>
<td>7.507866</td>
<td>2.3</td>
</tr>
<tr>
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<td>100</td>
<td>7.5844</td>
<td>7.2142</td>
<td>1.69</td>
</tr>
<tr>
<td>3</td>
<td>6000</td>
<td>300</td>
<td>8.6533</td>
<td>8.237066</td>
<td>3.8166</td>
</tr>
<tr>
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<td>3000</td>
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<td>100</td>
<td>8.31906</td>
<td>7.949566</td>
<td>2.565</td>
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</table>

7.10.2.3 Estimation of Correlation between Optical Roughness Parameters and Stylus Roughness Parameter

After calculating all the values of optical parameters ‘Ga’, before applying the filter to the images and ‘Gaf’, after applying the filter to the images, the correlation is found out with surface roughness, ‘Ra’, measured with stylus instrument. To achieve this purpose the graph is drawn between the optical surface roughness Ga (before applying the filter to the images) and stylus surface roughness, ‘Ra’ for the graphite specimen (density 1.541 g / cc) which is shown in figure 7.51. Another graph is drawn between the optical surface roughness, Gaf (after applying the filter to the images) and stylus surface roughness, ‘Ra’ for the same graphite specimen which is shown in figure 7.52.

Figure 7.51 shows that there is a good cubic correlation established between optical roughness parameter Ga (before applying filter) and stylus roughness ‘Ra’ for graphite specimen having density 1.541 g / cc. The relationship between ‘Ga’ and ‘Ra’ for graphite specimen having density 1.541 g / cc is

\[ Ga = 1.054 \times Ra^3 - 8.603 \times Ra^2 + 22.67 \times Ra - 11.19 \]  

Figure 7.52 shows that there is a better cubic correlation established between optical roughness parameter Gaf (after applying filter) and stylus roughness ‘Ra’ for graphite specimen having density 1.541 g / cc. Noise is reduced by applying filter to the images hence
Figure 7.49 3D Power spectrum of graphite 
(density = 1.541 g/cc) 
having Ra = 1.69 µm

Figure 7.50 3D Power spectrum of graphite 
(density = 1.541 g/cc) 
having Ra = 3.8166 µm

Figure 7.51 Correlation between stylus Ra 
and optical roughness Ga for 
graphite(density = 1.541 g/cc)

Figure 7.52 Correlation between stylus Ra 
and optical roughness Gaf for 
graphite(density = 1.541 g/cc)
better correlation is established. The relationship between ‘Gaf’ and ‘Ra’ for graphite specimen having density 1.541 g / cc is

\[ Gaf = 0.9336 \times Ra^3 - 7.644 \times Ra^2 + 20.26 \times Ra - 9.635 \]  
(7.12)

### 7.10.3 Conclusions

The result obtained confirmed that the histogram and power spectrum can be successfully applied to decide whether the analyzed surface is coarse or smooth. Hence acceptance or rejection policy of the components can be generated by that. As the surface becomes smoother, reflectivity increases resulting into increase in the frequency of larger value intensity of histogram. There is a higher value of amplitude of power spectrum as surface having higher value of roughness i.e. rough surface. As surface becomes smooth, the amplitude of power spectrum decreases.

It is established that there is a good cubic correlation between stylus parameter ‘Ra’ and optical parameter ‘Ga’. The correlation of ‘Gaf’, optical parameter after applying the Gaussian filter has a better cubic correlation with the average surface roughness ‘Ra’ measured using a conventional and widely accepted stylus type instrument for the graphite specimen having density 1.541 g / cc. After applying the filter, noise can be removed, which results in better cubic correlation between stylus roughness ‘Ra’ and optical roughness ‘Gaf’ for the graphite specimen having density 1.541 g / cc. The governing equations are

\[ Ga = 1.054 \times Ra^3 - 8.603 \times Ra^2 + 22.67 \times Ra - 11.19 \]  
(7.11)

\[ Gaf = 0.9336 \times Ra^3 - 7.644 \times Ra^2 + 20.26 \times Ra - 9.635 \]  
(7.12)

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7.11 Experiments Carried out on Graphite Specimen having Density 1.8478 g / cc

7.11.1 Experimental Procedure

Graphite specimen having density 1.8478 g / cc is machined on vertical machining center (VMC-850) with 12mm, four fluted end mill. Various surface roughnesses are obtained by controlling the machining parameters i.e. different speeds and feeds on VMC machine.

According to the capability of VMC – 850 machine available and general recommendation of machining condition for graphite, the following parameters shown in table 7.13 are selected.

<table>
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<td>4500</td>
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<td>5</td>
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<td>100</td>
</tr>
<tr>
<td>6</td>
<td>2000</td>
<td>300</td>
</tr>
</tbody>
</table>

The depth of cut of machining is set at 2 mm. The images of these machined specimens are grabbed by high resolution color CCD camera (Samsung SDC-313B) having effective pixels 768 (H) x 494 (V) with binocular stereo microscope (RSM 4).

Low pass filter is applied to all images. Histogram analysis and evaluation of optical surface roughness are carried out. Power spectrum is also obtained. These analyses are done with the help of image processing tool of Matlab. After completing the mentioned analysis, the arithmetic average roughness parameter is obtained for all specimens with the help of stylus roughness tester. Correlation is found out between measured stylus parameter and optical parameter.
7.11.2 Analysis of Result and Discussion

Analysis of each image is carried out. Here the images of graphite specimen (density 1.8478 g / cc) having stylus roughness, ‘Ra’ of 2.34 μm and 3.25 μm are shown in figures 7.53 and 7.54.

7.11.2.1 Histogram Analysis

Gray scale analysis technique has been used for surface characteristic which is known as histogram. Histogram drawn shows the variation of grey level intensity as per the surface roughness of the surface. It shows the occurrence (frequency) of grey level intensity over the surface. Figures 7.55 and 7.56 show histograms of images having different surface roughness.

As the surface becomes smoother, there is an increase in the frequency of larger value intensity. In histogram, left side shows the smaller value of intensities and right side shows the larger value of intensities. As surface becomes smooth, reflectivity increases, resulting in higher value of frequencies for larger gray value intensities. In figure 7.56, rougher surface having surface roughness Ra = 3.25 μm, there is a dominance of gray level 100 approximately having frequency (number of times each gray value occurs in image) 12000. However in the case of relatively smoother surface having surface roughness Ra = 2.34 μm, it is observed from figure 7.55 that 100 value of gray level is having 14000 frequency.

So from histogram one can judge that whether the surface is relatively smooth or rough. Histograms have the limitation that they carry no information regarding the relative position of the pixel intensities with respect to each other.
Figure 7.53 Image of graphite  
(density = 1.8478 g/cc)  
having Ra = 2.34 μm

Figure 7.54 Image of graphite  
(density = 1.8478 g/cc)  
having Ra = 3.25 μm

Figure 7.55 Histogram of graphite  
(density = 1.8478 g/cc)  
having Ra = 2.34 μm

Figure 7.56 Histogram of graphite  
(density = 1.8478 g/cc)  
having Ra = 3.25 μm
7.11.2.2 Fourier Analysis (Power Spectrum)

The 3-D perspective of the power spectrum of the surface image (after applying the filter) is to be shown in figures 7.57 and 7.58. It can be clearly seen from these figures that as surface roughness $'Ra'$ decreases, amplitude of power spectra is also decreased.

Power spectrum is a magnitude of Fourier transform of an image. As the surface becomes smoother i.e. roughness value decreases, then the amplitude of power spectrum also decreases. Figure 7.58 shows that amplitude of power spectrum of graphite specimen having roughness $Ra = 3.25 \, \mu m$ is $0.95 \times 10^{-10}$ while as shown in figure 7.57, the amplitude of power spectrum of graphite specimen having roughness $Ra = 2.34 \, \mu m$ is $0.8 \times 10^{-10}$.

7.11.2.3 Evaluation of Optical Roughness Parameter

With the help of image processing tool of MATLAB software, the optical roughness arithmetic average of gray level, $(Ga)$ is calculated using equations 5.4 and 5.5, for all the surfaces after capturing the images of surfaces.

Arithmetic average of the gray level $Ga$ (optical roughness) can be expressed as

$$Ga = \frac{\left( g_1 - g_m + g_2 - g_m + g_3 - g_m + \ldots + g_n - g_m \right)}{n} \quad (5.4)$$

Where $g_1, g_2, g_3, \ldots, g_n$ are the gray level values of a surface of image along one line and $g_m$ is the mean of the gray values and this can be determined as

$$g_m = \frac{\left( g_1 + g_2 + g_3 + \ldots + g_n \right)}{n} \quad (5.5)$$

After applying the low pass Gaussian filter to all images, again ‘Gaf’ is calculated. Finally ‘Ga’ values before applying filter and ‘Gaf’ values after applying the filter are compared with the respective ‘Ra’ values measured using a stylus instrument. To obtain the stylus roughness, ‘Ra’, the diamond stylus tip is moved over the machined surface of each specimen. Cut-off length is taken as 0.25 mm and total traverse length is 1.25 mm. Result of all calculated values ‘Ga’, ‘Gaf’ and measured ‘Ra’ for graphite specimens is shown in table 7.14.
TABLE 7.14

MACHINING PARAMETERS USED AND THE CORRESPONDING OPTICAL AND STYLUS ROUGHNESS VALUES FOR GRAPHITE SPECIMEN HAVING DENSITY 1.8478 g / cc

<table>
<thead>
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<th>S no</th>
<th>Speed (rpm)</th>
<th>Feed (mm/min)</th>
<th>$G_a$ (without filter)</th>
<th>$G_{af}$ (with filter)</th>
<th>$R_a$ (μm)</th>
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<td>10.9705</td>
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<td>3.25</td>
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<td>2</td>
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<td>100</td>
<td>7.3107</td>
<td>6.938633</td>
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<td>300</td>
<td>8.6708</td>
<td>8.2616</td>
<td>3.985</td>
</tr>
<tr>
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<td>2000</td>
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<td>7.8761</td>
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<td>2.34</td>
</tr>
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<td>5</td>
<td>2000</td>
<td>100</td>
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<td>300</td>
<td>7.642166</td>
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<td>2.675</td>
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7.11.2.3 Estimation of Correlation between Optical Roughness Parameters and Stylus Roughness Parameter

After calculating all the values of optical parameters ‘$G_a$’, before applying the filter to the images and ‘$G_{af}$’, after applying the filter to the images, the correlation is found out with surface roughness, ‘$R_a$’, measured with stylus instrument. To achieve this purpose the graph is drawn between the optical surface roughness $G_a$ (before applying the filter to the images) and stylus surface roughness, ‘$R_a$’ for the graphite specimen (density 1.8478 g / cc) which is shown in figure 7.59. Another graph is drawn between the optical surface roughnesses, $G_{af}$ (after applying the filter to the images) and stylus surface roughness, ‘$R_a$’ for the same graphite specimen which is shown in figure 7.60.

Figure 7.59 shows that there is a good cubic correlation established between optical roughness parameter $G_a$ (before applying filter) and stylus roughness ‘$R_a$’ for graphite specimen having density 1.8478 g / cc. The relationship between ‘$G_a$’ and ‘$R_a$’ for graphite specimen having density 1.8478 g / cc is

$$G_a = -7.059 \times R_a^3 + 66 \times R_a^2 - 200.5 \times R_a + 206.2 \quad (7.13)$$

Figure 7.60 shows that there is a better cubic correlation established between optical roughness parameter $G_{af}$ (after applying filter) and stylus roughness ‘$R_a$’ for graphite
Figure 7.57 3D Power spectrum of graphite (density = 1.8478 g/cc) having Ra = 2.34 μm

Figure 7.58 3D Power spectrum of graphite (density = 1.8478 g/cc) having Ra = 3.25 μm

Figure 7.59 Correlation between stylus Ra and optical roughness Ga for graphite (density = 1.8478 g/cc)

Figure 7.60 Correlation between stylus Ra and optical roughness Ga for graphite (density = 1.8478 g/cc)
specimen having density 1.8478 g / cc. Noise is reduced by applying filter to the images hence better correlation is established. The relationship between ‘Gaf’ and ‘Ra’ for graphite specimen having density 1.8478 g / cc is

\[ Gaf = -6.919 \times Ra^3 + 64.66 \times Ra^2 - 196.3 \times Ra + 201.4 \] (7.14)

7.11.3 Conclusions

The result obtained confirmed that the histogram and power spectrum can be successfully applied to decide whether the analyzed surface is coarse or smooth. Hence acceptance or rejection policy of the components can be generated by that. As the surface becomes smoother, reflectivity increases resulting into increase in the frequency of larger value intensity of histogram. There is a higher value of amplitude of power spectrum as surface having higher value of roughness i.e. rough surface. As surface becomes smooth, the amplitude of power spectrum decreases.

It is established that there is a good cubic correlation between stylus parameter ‘Ra’ and optical parameter ‘Ga’. The correlation of ‘Gaf’, optical parameter after applying the Gaussian filter has a better cubic correlation with the average surface roughness ‘Ra’ measured using a conventional and widely accepted stylus type instrument for the graphite specimen having density 1.8478 g / cc. After applying the filter, noise can be removed which results in better cubic correlation between stylus roughness ‘Ra’ and optical roughness ‘Gaf’ for the graphite specimen having density 1.8478 g / cc. The governing equations are

\[ Ga = -7.059 \times Ra^3 + 66 \times Ra^2 - 200.5 \times Ra + 206.2 \] (7.13)

\[ Gaf = -6.919 \times Ra^3 + 64.66 \times Ra^2 - 196.3 \times Ra + 201.4 \] (7.14)
7.12 Experiments Carried out on Graphite Specimen having Density 1.45 g / cc

7.12.1 Experimental Procedure

Graphite specimen having density 1.45 g / cc is machined on vertical machining center (VMC-850) with 12mm, four fluted end mill. Various surface roughnesses are obtained by controlling the machining parameters i.e. different speeds and feeds on VMC machine.

According to the capability of VMC - 850 machine available and general recommendation of machining condition for graphite, the following parameters shown in table 7.15 are selected.

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<td>4</td>
<td>7000</td>
<td>300</td>
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</tbody>
</table>

The depth of cut of machining is set as 2 mm. The images of these machined specimens are grabbed by high resolution color CCD camera (Samsung SDC-313B) having effective pixels 768 (H) x 494 (V) with binocular stereo microscope (RSM 4).

Low pass filter is applied to all images. Histogram analysis and evaluation of optical surface roughness are carried out. Power spectrum is also obtained. These analyses are done with the help of image processing tool of Matlab. After completing the mentioned analysis, the arithmetic average roughness parameter is obtained for all specimens with the help of stylus roughness tester. Correlation is found out between measured stylus parameter and optical parameter.
7.12.2 Analysis of Result and Discussion

Analysis of each image is carried out. Here the images of graphite specimen (density 1.45 g / cc) having stylus roughness, ‘Ra’ of 2.905 μm and 3.315 μm are shown in figures 7.61 and 7.62.

7.12.2.1 Histogram Analysis

Gray scale analysis technique has been used for surface characteristic which is known as histogram. Histogram drawn shows the variation of grey level intensity as per the surface roughness of the surface. It shows the occurrence (frequency) of grey level intensity over the surface. Figures 7.63 and 7.64 show histograms of images having different surface roughness.

As the surface becomes smoother, there is an increase in the frequency of larger value intensity. In histogram, left side shows the smaller value of intensities and right side shows the larger value of intensities. As surface becomes smooth, reflectivity increases, resulting in higher value of frequencies for larger gray value intensities. In figure 7.64, rougher surface having surface roughness Ra = 3.315 μm, there is a dominance of gray level 90 approximately having frequency (number of times each gray value occurs in image) 14000. However in the case of relatively smoother surface having surface roughness Ra = 2.905 μm, it is observed from figure 7.63 that 90 value of gray level is having 16000 frequency.

So from histogram one can judge that whether the surface is relatively smooth or rough. Histograms have the limitation that they carry no information regarding the relative position of the pixel intensities with respect to each other.
Figure 7.61 Image of graphite
(density = 1.45 g/cc)
having Ra = 2.905 μm

Figure 7.62 Image of graphite
(density = 1.45 g/cc)
having Ra = 3.315 μm

Figure 7.63 Histogram of graphite
(density = 1.45 g/cc)
having Ra = 2.905 μm

Figure 7.64 Histogram of graphite
(density = 1.45 g/cc)
having Ra = 3.315 μm
7.12.2.2 Fourier Analysis (Power Spectrum)

The 3-D perspective of the power spectrum of the surface image (after applying the filter) is to be shown in figures 7.65 and 7.66. It can be clearly seen from these figures that as surface roughness ‘Ra’ decreases, amplitude of power spectra is also decreased.

Power spectrum is a magnitude of Fourier transform of an image. As the surface becomes smoother i.e. roughness value decreases, then the amplitude of power spectrum also decreases. Figure 7.66 shows that amplitude of power spectrum of graphite specimen having roughness Ra = 3.315 µm is $0.85 \times 10^{10}$ while as shown in figure 7.65, the amplitude of power spectrum of graphite specimen having roughness Ra = 2.905 µm is $0.8 \times 10^{10}$.

7.12.2.3 Evaluation of Optical Roughness Parameter

With the help of image processing tool of MATLAB software, the optical roughness arithmetic average of gray level, (Ga) is calculated using equations 5.4 and 5.5, for all the surfaces after capturing the images of surfaces.

Arithmetic average of the gray level Ga (optical roughness) can be expressed as

$$Ga = \left( \frac{1}{n} \sum (|g_1 - g_m| + |g_2 - g_m| + |g_3 - g_m| + \ldots + |g_n - g_m|) \right)$$  \hspace{1cm} (5.4)

Where $g_1, g_2, g_3, \ldots, g_n$ are the gray level values of a surface of image along one line and $g_m$ is the mean of the gray values and this can be determined as

$$g_m = \left( \frac{1}{n} \sum (g_1 + g_2 + g_3 + \ldots + g_n) \right)$$  \hspace{1cm} (5.5)

After applying the low pass Gaussian filter to all images, again ‘Gaf’ is calculated. Finally ‘Ga’ values before applying filter and ‘Gaf’ values after applying the filter are compared with the respective ‘Ra’ values measured using a stylus instrument. To obtain the stylus roughness, ‘Ra’, the diamond stylus tip is moved over the machined surface of each specimen. Cut-off length is taken as 0.25 mm and total traverse length is 1.25 mm. Result of all calculated values ‘Ga’, ‘Gaf’ and measured ‘Ra’ for graphite specimens is shown in table 7.16.
### TABLE 7.16

MACHINING PARAMETERS USED AND THE CORRESPONDING OPTICAL AND STYLUS ROUGHNESS VALUES FOR GRAPHITE SPECIMEN HAVING DENSITY 1.45 g / cc

<table>
<thead>
<tr>
<th>S no</th>
<th>Speed (rpm)</th>
<th>Feed (mm/min)</th>
<th>( G_a ) (without filter)</th>
<th>( G_{af} ) (with filter)</th>
<th>( R_a ) (( \mu m ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7000</td>
<td>50</td>
<td>8.07636</td>
<td>7.7366</td>
<td>2.905</td>
</tr>
<tr>
<td>2</td>
<td>7000</td>
<td>100</td>
<td>9.37433</td>
<td>9.010766</td>
<td>3.315</td>
</tr>
<tr>
<td>3</td>
<td>7000</td>
<td>200</td>
<td>8.44816</td>
<td>8.07003</td>
<td>3.4</td>
</tr>
<tr>
<td>4</td>
<td>7000</td>
<td>300</td>
<td>7.05218</td>
<td>6.66706</td>
<td>3.435</td>
</tr>
</tbody>
</table>

### 7.12.2.4 Estimation of Correlation between Optical Roughness Parameters and Stylus Roughness Parameter

After calculating all the values of optical parameters ‘\( G_a \)’, before applying the filter to the images and ‘\( G_{af} \)’, after applying the filter to the images, the correlation is found out with surface roughness, \( R_a \), measured with stylus instrument. To achieve this purpose the graph is drawn between the optical surface roughness \( G_a \) (before applying the filter to the images) and stylus surface roughness, \( R_a \) for the graphite specimen (density 1.45 g / cc) which is shown in figure 7.67. Another graph is drawn between the optical surface roughness, \( G_{af} \) (after applying the filter to the images) and stylus surface roughness, \( R_a \) for the same graphite specimen which is shown in figure 7.68.

Figure 7.67 shows that there is a good quadratic correlation established between optical roughness parameter \( G_a \) (before applying filter) and stylus roughness \( R_a \) for graphite specimen having density 1.45 g / cc. The relationship between ‘\( G_a \)’ and ‘\( R_a \)’ for graphite specimen having density 1.45 g / cc is

\[
G_a = - 41.28 \times R_a^2 + 260.3 \times R_a - 399.6 \tag{7.15}
\]

Figure 7.68 shows that there is a better quadratic correlation established between optical roughness parameter \( G_{af} \) (after applying filter) and stylus roughness \( R_a \) for graphite specimen having density 1.45 g / cc. Noise is reduced by applying filter to the
Figure 7.65 3D Power spectrum of graphite
(density = 1.45 g/cc)
having Ra = 2.905 μm

Figure 7.66 3D Power spectrum of graphite
(density = 1.45 g/cc)
having Ra = 3.315 μm

Figure 7.67 Correlation between stylus Ra and optical roughness Ga for graphite (density = 1.45 g/cc)

Figure 7.68 Correlation between stylus Ra and optical roughness Gaf for graphite (density = 1.45 g/cc)
images hence better correlation is established. The relationship between ‘Gaf’ and ‘Ra’ for graphite specimen having density 1.45 g / cc is

\[ Gaf = -41.51 \times Ra^2 + 261.6 \times Ra - 402 \quad (7.16) \]

7.12.3 Conclusions

The result obtained confirmed that the histogram and power spectrum can be successfully applied to decide whether the analyzed surface is coarse or smooth. Hence acceptance or rejection policy of the components can be generated by that. As the surface becomes smoother, reflectivity increases resulting into increase in the frequency of larger value intensity of histogram. There is a higher value of amplitude of power spectrum as surface having higher value of roughness i.e. rough surface. As surface becomes smooth, the amplitude of power spectrum decreases.

It is established that there is a good quadratic correlation between stylus parameter ‘Ra’ and optical parameter ‘Ga’. The correlation of ‘Gaf’, optical parameter after applying the Gaussian filter has a better quadratic correlation with the average surface roughness ‘Ra’ measured using a conventional and widely accepted stylus type instrument for the graphite specimen having density 1.45 g / cc. After applying the filter, noise can be removed, which results in better quadratic correlation between stylus roughness ‘Ra’ and optical roughness ‘Gaf’ for the graphite specimen having density 1.45 g / cc. The governing equations are

\[ Ga = -41.28 \times Ra^2 + 260.3 \times Ra - 399.6 \quad (7.15) \]

\[ Gaf = -41.51 \times Ra^2 + 261.6 \times Ra - 402 \quad (7.16) \]
7.13 Experiments Carried out on Graphite Specimen having Density 1.7082 g / cc

7.13.1 Experimental Procedure

Graphite specimen having density 1.7082 g / cc is machined on vertical machining center (VMC-850) with 12mm, four fluted end mill. Various surface roughnesses are obtained by controlling the machining parameters i.e. different speeds and feeds on VMC machine.

According to the capability of VMC – 850 machine available and general recommendation of machining condition for graphite, the following parameters shown in table 7.17 are selected.

<table>
<thead>
<tr>
<th>S no</th>
<th>Speed (rpm)</th>
<th>Feed (mm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3000</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>3000</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>3000</td>
<td>200</td>
</tr>
<tr>
<td>4</td>
<td>3000</td>
<td>300</td>
</tr>
<tr>
<td>5</td>
<td>1000</td>
<td>50</td>
</tr>
</tbody>
</table>

The depth of cut of machining is set as 2 mm. The images of these machined specimens are grabbed by high resolution color CCD camera (Samsung SDC-313B) having effective pixels 768 (H) x 494 (V) with binocular stereo microscope (RSM 4).

Low pass filter is applied to all images. Histogram analysis and evaluation of optical surface roughness are carried out. Power spectrum is also obtained. These analyses are done with the help of image processing tool of Matlab. After completing the mentioned analysis, the arithmetic average roughness parameter is obtained for all specimens with the help of stylus roughness tester. Correlation is found out between measured stylus parameter and optical parameter.
7.13.2 Analysis of Result and Discussion

Analysis of each image is carried out. Here the images of graphite specimen (density 1.7082 g/cc) having stylus roughness, ‘Ra’ of 3.64 µm and 4.355 µm are shown in figures 7.69 and 7.70.

7.13.2.1 Histogram Analysis

Gray scale analysis technique has been used for surface characteristic which is known as histogram. Histogram drawn shows the variation of grey level intensity as per the surface roughness of the surface. It shows the occurrence (frequency) of grey level intensity over the surface. Figures 7.71 and 7.72 show histograms of images having different surface roughness.

As the surface becomes smoother, there is an increase in the frequency of larger value intensity. In histogram, left side shows the smaller value of intensities and right side shows the larger value of intensities. As surface becomes smooth, reflectivity increases, resulting in higher value of frequencies for larger gray value intensities. In figure 7.72, rougher surface having surface roughness Ra = 4.355 µm, there is a dominance of gray level 100 approximately having frequency (number of times each gray value occurs in image) 12000. However in the case of relatively smoother surface having surface roughness Ra = 3.64 µm, it is observed from figure 7.71 that 100 value of gray level is having 14000 frequency.

So from histogram one can judge that whether the surface is relatively smooth or rough. Histograms have the limitation that they carry no information regarding the relative position of the pixel intensities with respect to each other.
Figure 7.69 Image of graphite (density = 1.7082 g/cc) having Ra = 3.64 μm

Figure 7.70 Image of graphite (density = 1.7082 g/cc) having Ra = 4.355 μm

Figure 7.71 Histogram of graphite (density = 1.7082 g/cc) having Ra = 3.64 μm

Figure 7.72 Histogram of graphite (density = 1.7082 g/cc) having Ra = 4.355 μm
7.13.2.2 Fourier Analysis (Power Spectrum)

The 3-D perspective of the power spectrum of the surface image (after applying the filter) is to be shown in figures 7.73 and 7.74. It can be clearly seen from these figures that as surface roughness ‘Ra’ decreases, amplitude of power spectra is also decreased.

Power spectrum is a magnitude of Fourier transform of an image. As the surface becomes smoother i.e. roughness value decreases, then the amplitude of power spectrum also decreases. Figure 7.74 shows that amplitude of power spectrum of graphite specimen having roughness Ra = 4.355 μm is $1.0 \times 10^{10}$ while as shown in figure 7.73, the amplitude of power spectrum of graphite specimen having roughness Ra = 3.64 μm is $8 \times 10^9$.

7.13.2.3 Evaluation of Optical Roughness Parameter

With the help of image processing tool of MATLAB software, the optical roughness arithmetic average of gray level, (Ga) is calculated using equations 5.4 and 5.5, for all the surfaces after capturing the images of surfaces.

Arithmetic average of the gray level Ga (optical roughness) can be expressed as

$$Ga = \left( \sum (|g_1 - g_m| + |g_2 - g_m| + |g_3 - g_m| + \ldots + |g_n - g_m|) \right)/n \quad (5.4)$$

Where $g_1, g_2, g_3, \ldots, g_n$ are the gray level values of a surface of image along one line and $g_m$ is the mean of the gray values and this can be determined as

$$g_m = \left( \sum (g_1 + g_2 + g_3 + \ldots + g_n) \right)/n \quad (5.5)$$

After applying the low pass Gaussian filter to all images, again ‘Gaf’ is calculated. Finally ‘Ga’ values before applying filter and ‘Gaf’ values after applying the filter are compared with the respective ‘Ra’ values measured using a stylus instrument. To obtain the stylus roughness, ‘Ra’, the diamond stylus tip is moved over the machined surface of each specimen. Cut-off length is taken as 0.25 mm and total traverse length is 1.25 mm. Result of all calculated values ‘Ga’, ‘Gaf’ and measured ‘Ra’ for graphite specimens is shown in table 7.18.
TABLE 7.18
MACHINING PARAMETERS USED AND THE CORRESPONDING OPTICAL AND STYLUS ROUGHNESS VALUES FOR GRAPHITE SPECIMEN HAVING DENSITY 1.7082 g / cc

<table>
<thead>
<tr>
<th>S no</th>
<th>Speed (rpm)</th>
<th>Feed (mm/min)</th>
<th>( G_a ) (without filter) ( G_{af} ) (with filter)</th>
<th>( R_a ) (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3000</td>
<td>50</td>
<td>7.9059</td>
<td>7.581033</td>
</tr>
<tr>
<td>2</td>
<td>3000</td>
<td>100</td>
<td>8.5616</td>
<td>8.13173</td>
</tr>
<tr>
<td>3</td>
<td>3000</td>
<td>200</td>
<td>9.1078</td>
<td>8.65453</td>
</tr>
<tr>
<td>4</td>
<td>3000</td>
<td>300</td>
<td>9.09846</td>
<td>8.7801</td>
</tr>
<tr>
<td>5</td>
<td>1000</td>
<td>50</td>
<td>10.0308</td>
<td>9.542</td>
</tr>
</tbody>
</table>

7.13.2.4 Estimation of Correlation between Optical Roughness Parameters and Stylus Roughness Parameter

After calculating all the values of optical parameters ‘\( G_a \)’, before applying the filter to the images and ‘\( G_{af} \)’, after applying the filter to the images, the correlation is found out with surface roughness, ‘\( R_a \)’, measured with stylus instrument. To achieve this purpose the graph is drawn between the optical surface roughness \( G_a \) (before applying the filter to the images) and stylus surface roughness, ‘\( R_a \)’ for the graphite specimen (density 1.7082 g / cc) which is shown in figure 7.75. Another graph is drawn between the optical surface roughness, \( G_{af} \) (after applying the filter to the images) and stylus surface roughness, ‘\( R_a \)’ for the same graphite specimen which is shown in figure 7.76.

Figure 7.75 shows that there is a good cubic correlation established between optical roughness parameter \( G_a \) (before applying filter) and stylus roughness ‘\( R_a \)’ for graphite specimen having density 1.7082 g / cc. The relationship between ‘\( G_a \)’ and ‘\( R_a \)’ for graphite specimen having density 1.7082 g / cc is

\[
G_a = -26.4 \times R_a^3 + 313.8 \times R_a^2 - 1237 \times R_a + 1626 \quad (7.17)
\]

Figure 7.76 shows that there is a better cubic correlation established between optical roughness parameter \( G_{af} \) (after applying filter) and stylus roughness ‘\( R_a \)’ for graphite specimen having density 1.7082 g / cc. Noise is reduced by applying filter to the images hence better correlation is established. The relationship between ‘\( G_{af} \)’ and ‘\( R_a \)’ for graphite
Figure 7.73 3D Power spectrum of graphite (density = 1.7082 g/cc) having Ra = 3.64 μm

Figure 7.74 3D Power spectrum of graphite (density = 1.7082 g/cc) having Ra = 4.355 μm

Figure 7.75 Correlation between stylus Ra and optical roughness Ga for graphite (density = 1.7082 g/cc)

Figure 7.76 Correlation between stylus Ra and optical roughness Gaf for graphite (density = 1.7082 g/cc)
specimen having density 1.7082 g/cc is

\[
    \text{Ga} = -25.02 \times \text{Ra}^3 + 297.8 \times \text{Ra}^2 - 1176 \times \text{Ra} + 1548 \tag{7.18}
\]

### 7.13.2 Conclusions

The result obtained confirmed that the histogram and power spectrum can be successfully applied to decide whether the analyzed surface is coarse or smooth. Hence acceptance or rejection policy of the components can be generated by that. As the surface becomes smoother, reflectivity increases resulting into increase in the frequency of larger value intensity of histogram. There is a higher value of amplitude of power spectrum as surface having higher value of roughness i.e. rough surface. As surface becomes smooth, the amplitude of power spectrum decreases.

It is established that there is a good cubic correlation between stylus parameter ‘Ra’ and optical parameter ‘Ga’. The correlation of ‘Gaf’, optical parameter after applying the Gaussian filter has a better cubic correlation with the average surface roughness ‘Ra’ measured using a conventional and widely accepted stylus type instrument for the graphite specimen having density 1.7082 g/cc. After applying the filter, noise can be removed, which results in better cubic correlation between stylus roughness ‘Ra’ and optical roughness ‘Gaf’ for the graphite specimen having density 1.7082 g/cc. The governing equations are

\[
    \text{Ga} = -26.4 \times \text{Ra}^3 + 313.8 \times \text{Ra}^2 - 1237 \times \text{Ra} + 1626 \tag{7.17}
\]

\[
    \text{Ga} = -25.02 \times \text{Ra}^3 + 297.8 \times \text{Ra}^2 - 1176 \times \text{Ra} + 1548 \tag{7.18}
\]

This analysis shows that density of the graphite specimen influences stylus roughness parameter and optical roughness parameters when graphite specimens are machined under the same machining conditions. Stylus roughness parameter ‘Ra’ and optical roughness parameters, ‘Ga’ and ‘Gaf’ decrease with increase in density. Hence, a graphite specimen of higher density has comparatively smoother surface. The results obtained confirm that non-contact digital image processing can be successfully implemented in order to accept or reject the components of graphite specimen according to the characteristics of the surface in question.